TERRAIN PORTRAYAL FOR HEAD-DOWN DISPLAYS SIMULATION RESULTS

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Abstract

The Synthetic Vision Systems General Aviation (SVS-GA) element of NASA's Aviation Safety Program is developing technology to eliminate low visibility induced General Aviation (GA) accidents through the application of synthetic vision techniques. SVS displays present computer generated 3-dimensional imagery of the surrounding terrain to greatly enhance pilot's situation awareness (SA), reducing or eliminating Controlled Flight into Terrain (CFIT), as well as Low-Visibility Loss of Control (LVLOC) accidents.

A critical component of SVS displays is the appropriate presentation of terrain to the pilot. The relationship between the realism of the terrain presentation and resulting enhancements of pilot SA and pilot performance has been largely undefined. Comprised of coordinated simulation and flight test efforts, the terrain portrayal for head-down displays (TP-HDD) test series examined the effects of two primary elements of terrain portrayal: variations of digital elevation model (DEM) resolution and terrain texturing. Variations in DEM resolution ranged from sparsely spaced (30 arc-sec) to very closely spaced data (1 arc-sec). Variations in texture involved three primary methods: constant color, elevation-based generic, and photo-realistic, along with a secondary depth cue enhancer in the form of a fishnet grid overlay.

The TP-HDD simulation experiment addressed multiple objectives involving twelve display concepts (two baseline concepts without terrain and ten SVS variations), four evaluation maneuvers (two en route and one approach maneuver, plus a rare event scenario), and three pilot group classifications. Because of the complexity of this experiment, it is not practical to report on every significant aspect of the simulation in this paper. This paper provides a preview of simulation results by evaluating current technology (basic round dials) as it compared to the next level of display concept, an integrated primary flight display (PFD) (blue sky/brown ground), and continuing to the comparison of the SVS-PFD display concepts, almost exclusively for the approach maneuver.

Introduction

GA aircraft comprise 85 percent of the total number of civil aircraft in the United States of America (USA). In a report of the National Transportation Safety Board (NTSB) accident database [1], GA accounted for 85 percent of all accidents and 65 percent of all fatalities. The combination of night and IMC increased the proportion of fatal to total accidents to 64.3 percent, making it the most deadly general aviation flight environment.

The ability of a pilot to ascertain critical information through visual perception of the outside environment is limited by various weather phenomena, such as rain, fog, and snow. Since the beginning of flight, the aviation industry has continuously developed various devices to overcome low-visibility issues, such as attitude indicators, radio navigation, and instrument landing systems. Recent advances include moving map displays, incorporating advances in navigational accuracies from the Global Positioning System, and enhanced ground proximity warning systems. However, all of the aircraft information display concepts developed to date require the pilot to perform various additional levels of mental model development and maintenance and information decoding in a real-time environment when outside visibility is restricted [2].

SVS technology will allow this *visibility* problem to be solved with a *visibility* solution, as better pilot SA during low visibility conditions can be provided by synthetic vision displays. These displays employ computer-generated terrain imagery to present three dimensional, perspective, out the window scenes with sufficient information and realism to enable operations equivalent to those of a bright, clear day, regardless of the outside weather condition [2 through 12].

An essential component of all SVS displays is the synthetic terrain. SVS terrain provides information to the pilot regarding the outside world and also serves as the backdrop for integration of the other elements of the display (such as flight data information, guidance symbology, etc.). Effective terrain presentation, that conveys the optimum information to the pilot with the lowest mental workload, is paramount to successful SVS development and implementation.

Numerous publications [2 through 12] are available describing various terrain depiction techniques for tactical displays (PFD, HUD) and strategic ND and Multi-Function Displays (MFDs). These techniques include, but are not limited to, ridge lines, grid patterns (equal and non-equal spacing), color-coded contour lines, varying color textures based on elevation, photorealistic textures, and textures with an embedded grid pattern. Textures increase terrain realism by increasing the level of detail per polygon, thus providing additional cues for position and closure rate (height and range) estimates. Flight tests have demonstrated that adding a textured terrain skin to the EADIs and PFDs gave pilots a better awareness of their height above the ground. However, references 2 through 12 did not comprehensively investigate terrain portrayal techniques as applied to SVS displays, providing only information for specific cases, with limited comparisons.

Recently conducted work at the University of Iowa [11] provides detailed information regarding SVS terrain portrayal. In this study, a broad spectrum of terrain portrayal techniques were examined using several types of experimentation methods, including static and dynamic display evaluations combined with piloted simulations of a perspective terrain display located next to an EADI. The objective of reference 11 was to establish the minimum effective terrain portrayal technique to maximize the use of currently certified computer platforms with limited capabilities. Reference 11 provides a wealth of data regarding human perception of SVS terrain portrayal techniques and shows that terrain resolution and texturing significantly affect human subjects' ability to maintain SA.

The TP-HDD test series extends previous research on the effects of DEM resolution and texturing and includes real-time piloted simulation and flight test evaluations, with integrated SVS terrain and symbology, on primary flight displays. Only simulation results are presented here-in.

Objectives of TP-HDD Simulation

The TP-HDD test series was conducted to address several critical aspects of SVS displays, concentrating on core technology issues while identifying and addressing key certification issues. The objectives of the TP-HDD test series were to: 1) determine the effect of terrain texturing on situation awareness (SA) and pilot performance for SVS PFDs; 2) determine the effect of DEM resolution on SA and pilot performance for SVS PFDs; 3) establish field of view (FOV) recommendations for SVS PFDs; 4) demonstrate of the efficacy of SVS displays for a comprehensive spectrum of pilots in both mountainous and flat-maritime environments, 5) demonstrate that non-instrument rated pilots are able to fly to an acceptable level of precision, with minimal training, using an SVS PFDs with tunnel guidance symbology.

Method

To address these multiple objectives and a few other interesting issues (e.g., fish net and tunnel in the sky effectiveness), a complex experiment involving twelve display concepts (two without terrain and ten SVS variations), four evaluation maneuvers (two en route and one approach maneuver, plus a rare event scenario), and three pilot group classifications was conducted.

Terrain Databases

The terrain databases utilized for the results presented herein were generated for an area around Roanoke, Virginia (FAA airport identifier, ROA).

Digital Elevation Models (DEMs)

DEM resolution defines the distance between elevation data points (post-spacing) for a given database. Three specific DEM resolutions were investigated during the TP-HDD experiment to cover a broad range of viable DEM options. The low resolution, 30 arc-sec (900m/2,953ft post-spacing) DEM was selected because it is freely available and currently used in some industry SVS applications due to the low computational power required for rendering. The medium resolution, 3 arc-second (90m/295ft post-spacing) DEM was selected since it is also relatively available, or should be in the near future. The highest resolution, 1 arc-sec (30m/98ft post-spacing) DEM option was investigated to form an upper bound for current consideration.

It should be noted that higher resolution databases are much larger in terms of the overall number of data points for a given area of coverage with higher computational expenses associated with manipulating and rendering these data. In addition, the smallest polygon that can be created with a given DEM has sides equal to the distance between data points. For example, the smallest possible polygon employed with the 30 arc-sec DEM would have sides 2,953 feet long. Since the lower resolution DEMs are less populated, substantial terrain features might be excluded. The possibility of losing entire peaks as well as detailed terrain relief in the lower resolution databases exists.

Terrain-Texturing Concepts

Terrain-texturing refers to the method used to fill the polygons that comprise the terrain database. The three primary texturing concepts tested were constant-color (CC), elevation-based generic (EBG), and photo-realistic (PR). The CC texturing concept represented an industry concept that has completed the process of Federal Aviation Administration (FAA) certification in the Capstone-2 program. This texturing concept requires the least amount of computational resources for rendering (of textures evaluated in this experiment), enhancing the potential use of currently certified avionics platforms for SVS applications.

The EBG texturing concept consisted of twelve equal-height coloring bands that correspond to different absolute terrain elevation levels, similar to the colors employed for Visual Flight Rules (VFR) sectional charts. Lower terrain levels are colored with darker colors, higher terrain levels are assigned lighter colors. A certain shade of green was set to the field elevation. The lightest color was set to the highest terrain within 50 nm of ROA, approximately 4,000 ft MSL.

The PR texturing concept was created by overlaying color ortho-rectified 4m satellite imagery data onto a DEM database. The resulting scene was a realistic view of the ROA area. PR texturing requires special graphics hardware because of the amount of texture memory required to render the scene in real-time.

Cultural Feature Data

For the CC and EBG terrain textured display concepts, cultural features, such as roads and rivers, were included as objects in the terrain database. For the PR concepts, cultural and feature data were supplied naturally through the photo-texture images.

Fish Net Overlay Concept

In addition to the primary terrain texturing concepts, a fishnet (FN) grid overlay was added to several display concepts. The theory of the FN grid involves placing grids of known size within the synthetic scene to facilitate pilot's depth perception. The potential benefits of the FN grid are cues for depth perception, distance, angular orientation and angular rates. The spacing of the FN overlay was 500 ft by 500 ft, regardless of the DEM resolution. The FN grid was dual-color (gray/white) to compensate for different coloring of features within the terrain databases (e.g., lighter colors of populated areas for the PR texture).

Airport Models and Objects

The ROA airport model included runways with all runway markings along with most significant airport buildings. Airport buildings were developed to appear like the actual buildings they represented if viewed from approximately 3 miles. All models were placed on top of the underlying terrain database. Objects/obstacles greater then 200 ft high within 20 nm of ROA were represented by narrow rectangular barber-striped pole objects indicating their respective estimated heights and locations.

Display Types

The displays evaluated in the TP-HDD experiment were grouped into three types.

Blue Sky/Brown Ground PFD:

One type of display replicated conventional PFD's and was referred to as the blue-sky/brown ground (BSBG) concept. PFDs feature integrated information (i.e. airspeed, altitude, attitude) into one display.

Synthetic Vision Systems PFD:

SVS displays were identical in format to the conventional PFD, with the exception that various SVS terrain portrayals replaced the blue-sky/brown-ground background. The terrain portrayal concepts were developed from combinations of DEM resolutions and texturing methods. A total of 10 SVS display-concepts (DCs) were evaluated for this simulation experiment (Table 1).

Table 1. Evaluated SVS Display Concepts

Texture\DEM	30 arc-sec	3 arc-sec	1 arc-sec
CCFN	√		√
EBG			√
PR			√
EBGFN	√	√	√
PRFN	√	√	√

Figures 1 through 5 illustrate samples of the display concepts evaluated, all from the same perspective view. Figure 1 shows the CCFN texturing concept with 30 arc-sec DEM (CCFN30), representing a typical present-day GA application of SVS technology. Figures 2 and 3 show the EBG texturing concept with FN overlay, at DEM resolutions of 3 and 30 arc-sec (EBGFN3, EBGFN30). Figures 4 and 5 show the PR texturing concept with the FN overlay at DEM resolutions of 3 and 30 arc-sec (PRFN3, PRFN30). While the FN was designed to enhance the EBG and PR primary texturing concepts, it was determined to be essential for CC texturing due to the low amount of terrain information visible without it.

Baseline Round Dials:

Another type of display was referred to as the baseline round dials (BRD) and is shown in figure 6. The BRD type replicates instrumentation currently found in the vast majority of GA aircraft, including airspeed, attitude, altitude, turn coordinator, directional gyro, and vertical speed indicators. For the approach maneuver, course deviation indicators were also present, along side of the attitude indicator.

Symbology

On the PFD, symbology for all display concepts featured advanced GA symbology elements (see figure 7). Air-data information was presented by integrated airspeed and altitude tapes. Airspeed trend information was also included in the airspeed tape by a green bar that indicated the expected airspeed in 10 seconds. A vertical speed indicator was included in the integrated altitude tape. A roll pointer with a sideslip wedge and magnetic heading digital read-out, and a pitch ladder provided heading and attitude information. Additionally, a velocity vector cluster was present, utilizing a non-quickened velocity vector that depicted current aircraft flight path and track angle with an acceleration-along-flight-path indicator (off the left finlet of the velocity vector marker).

Additional symbology was presented for the approach maneuver. Course deviation indicators and a tunnel in the sky concept provided guidance information on the PFD. Vertical and lateral dogbone-shaped path deviation indicators supplied the pilot with information regarding proximity of the aircraft to the center of the tunnel. Diamond-shaped course deviation indicators were provided to show localizer and glideslope error. Both the dogbone-shaped path deviation indicators and diamond-shaped localizer/glideslope error deviation indicators were co-located on the same scales.

With computer-generated 3-dimensional imagery, SVS display concepts can provide pilot-selectable display Field of View (FOV) control to enhance display effectiveness [4]. For this experiment, FOV refers to the horizontal field of view of the image presented on the PFD unless otherwise specified. Vertical FOV was adjusted to be consistent with horizontal FOV and the research PFD's 4:3 aspect ratio. Pilots could select one of four FOVs: 22.5, 30, 60, and 90 degrees. The minification factor (MF) is defined as the amount of angular compression created when non-conformal imagery is displayed and is calculated by dividing the FOV by the conformal FOV of the display device. For this experiment, the MFs tested were: 2.0, 2.7, 5.5, and 8.2, respectively. MFs greater than unity make terrain features appear further away than they are in reality.

A tunnel in the sky concept was employed during the approach maneuver for all but one SVS display concept (used for a within concept on/off tunnel comparison) and the baseline round dials concept. The tunnel in the sky concept featured a series of unconnected 400 feet wide by 320 feet tall uniform green rectangles depicting the desired flight path for the approach scenario, providing most of the lateral and vertical path guidance. Tunnel spacing was dependent on FOV, influenced by a design implemented by a current industry concept. For the wider FOV's, the tunnel boxes were closer together; for the smaller FOV's, the tunnel boxes were spaced farther apart (i.e.: FOV=90°, distance between boxes was 965 ft; FOV=30°, distance between boxes was 4,685 ft). During turns, if the required bank angle was greater than 5°, the boxes were tilted 20° to cue the turn.

For the baseline round dials concept, the symbology was similar to that of a traditional GA instrument panel: airspeed indicator, attitude indicator, altimeter, turn coordinator, directional gyroscope, vertical speed indicator, and an rpm gauge. For approach guidance, localizer and glide slope information was available adjacent to the attitude indicator.

Strategic Display

Strategic terrain display information was provided by an United Parcel Service Aviation Technology (UPSAT) MX-20 MFD located in the radio stack. On the MX-20 MFD, terrain awareness, route information, waypoints, and towers were portrayed (Figure 8). All display concepts were evaluated in the presence of the MX-20 MFD. Terrain more than 2,000 ft below the aircraft was portrayed in black, terrain between 2,000 ft and 500 ft was green, terrain between 500 ft and ownship altitude was yellow, terrain at or above ownship altitude was red.

Simulator

The experiment was conducted using the fixed-base NASA LaRC General Aviation Work Station (GAWS, figure 9). The GAWS facility was based on a modified Precision Flight Control PC-based Aviation Training Device (PCATD) Model PI-142 instrument procedure trainer. The evaluation pilot (EP) flew in the left seat and utilized yoke and pedals, power quadrant, and floor-mounted radio stack. Primary elements of the GAWS instrument panel were: UPSAT MX-20 MFD, UPSAT GX-50, 15" Research BRD, 6" Research PFD, and out-the-window (OTW) view.

A Pentium-3 class PC hosted the Initiative Computing Electronic IFR Training Environment (ELITE) Version 6.2 software. The ELITE software provided the aircraft dynamic responses to pilot control inputs, and control of the out-the-window visibility, as well as data required to generate the research display imagery. ELITE software simulated a generic Cessna-172 model in this experiment.

Intergraph Zx10 dual-processor graphics workstations generated the OTW and Head-Down display imagery. Both Zx10 computers included dual 1-GHz processors with 1 Gigabytes of random access memory (RAM), 60 G-byte hard-drive, and 3DLab's Wildcat 4210 graphics cards.

The 15" Research BRD displayed seven 3" diameter gauges using an XGA format (1024 by 768), and provided at least 85 ppi. The research PFD was a COTS Computer Dynamics 6" high-bright 4:3 aspect ratio Liquid Crystal Display (LCD), operated in VGA mode (640x480), 256K colors. The display was repackaged for this study.

Out The Window Scene

A front visual scene was projected on a screen (7 ft wide by 6 ft tall) located approximately 6 feet beyond the pilot instrument panel. While sitting in the left seat of the simulator, the EP maintained a horizontal pilot viewing angle of approximately 41° and a vertical pilot viewing angle of around 29° of the emulated out the window scenes. The highest fidelity photo-realistic research terrain database (1 arc-sec) was employed for the OTW scene. The front visual scene was also capable of simulating weather to the extent of creating IMC and transitioning from VMC to IMC.

Field of View Control

For the PFD and SVS-PFD concepts, the pilots could adjust the field of view (FOV). Pilots were able to select from four FOVs through a rotary knob, located adjacent to the lower left corner of the research PFD, or a push-button switch, located on the yoke. Symbology was changed to remain conformal to the terrain for the various FOVs.

Evaluation Maneuvers

The evaluation maneuvers were developed to cover critical phases of flight. To add some additional sensation of realism and more representative levels of workload, a low/moderate level of turbulence was simulated throughout each run.

En Route Maneuver

Two en route maneuvers were flown which required the evaluation pilot to maintain assigned heading, airspeed, and altitude values at different points during a 5-minute task. The en route maneuvers began 19 nautical miles (nm) southwest of ROA, with a heading of 140° and an indicated airspeed of 100 knots (KIAS). The high altitude en route task was initiated at 9,500 ft MSL (approximately 7,000ft above ground level (AGL)), while the low altitude en route maneuver began at 6,500 ft MSL (approximately 4,000 ft AGL). For both maneuvers, pilots were required to fly straight and level for approximately 2.5 minutes, maintaining heading, airspeed, and altitude. With the help of the strategic display to identify a fly-by waypoint, the EPs then executed a left turn, using 20 degrees of bank, to a heading of 050°, while simultaneously descending 1,500 ft (over rising terrain). For this maneuver, part of the descent took place during the 90° turn, and the rest of the descent was completed while maintaining the second target heading. The target level-off altitude for the high altitude task was 8,000 ft MSL (approximately 4,000 ft AGL), while the target altitude for the low altitude task was 5,000 ft MSL (approximately 1,000 ft AGL).

At the starting point of the maneuver, VMC was simulated. One minute into the flight a one-minute transition into IMC was simulated by reduction of visibility on the OTW display to one statute mile. EPs were asked to vary FOV during the entire maneuver to any desired setting. At the end of the maneuver, the EPs were asked to cycle through FOVs, one more time, to support their evaluations.

Approach Maneuver

The approach maneuver consisted of a 6.5-minute flight simulation starting with a straight and level flight on a 30-degree localizer intercept course for the Instrument Landing System (ILS) 33 approach into ROA. The target indicated airspeed throughout the maneuver was 90 knots. The subject pilots were tasked to fly a heading of approximately 300° to join the localizer (roughly 10 nm from the threshold) and maintain 2,640 ft until intercepting the glide slope at approximately 4.5 nm, then continue flying the approach to 200 ft AGL (1379 ft MSL). This initial altitude provided about a 400 ft clearance over a ridgeline that was traversed on the ILS intercept segment. During runs where the tunnel was present on the PFD, the EPs flew the tunnel for guidance. Out the window visibility was reduced from VMC to one statue mile within the first minute of the flight. In addition to moderate turbulence that decreased throughout the run, wind was simulated to be from 030° at 15 knots, decreasing to 5 knots on late-final approach. EPs were asked to vary FOV during the entire maneuver to any desired setting.

Rare Event

'Rare event' simulation techniques require many nominal simulation trials to produce only a few trials containing the data of interest. As employed for this effort, rare event testing attempted to generate high-quality data reflecting when pilots were exposed to a completely unexpected event of significant research interest. The purpose of this maneuver was to determine if SVS PFD concepts provided terrain SA sufficient to avoid CFIT accidents in an unexpected situation.

The rare event task simulated a flight scenario with an incorrect altimeter setting. Effectively, the altitude tape indicated the incorrect (higher) altitude, which was different from the actual altitude portrayed by the terrain on the PFD. In addition, the altitude provided to the MX-20 also included the same 1,500 ft error. This task was administered as the last run of the data collection for each evaluation pilot and was designed to look like the low altitude en route task. The evaluation pilots were not alerted to the rare event and thought they were just re-running a previous test condition.

The rare event maneuver started at the same position as the low altitude en route task, but at an altitude 1,500 ft lower. Consequently, the target level-off altitude was 500 ft below several mountaintops directly in front of the aircraft. Display concepts (excluding baseline concepts) were randomized among pilots repeating one of the display concepts already flown.

Participants

Twenty-seven pilots, categorized into three different experience levels, participated in the TP-HDD simulation. The first group consisted of fourteen low-time pilots, each with less than 400 hours and no instrument training beyond that required for the private pilot's license rating. Six instrument rated pilots with less than 1000 hours comprised the second group. The last group consisted of four professional test pilots from NASA, Boeing, and the FAA, and three Juneau (Alaska) area commercial operators; each having a total flight time of over 1000 hours. Pilots from Juneau, Alaska, were included in this experiment due to their experience with operations in that area, combined with being potential SVS users as part of the FAA Capstone-2 project.

Test Matrix

Each pilot evaluated the 10 SVS concepts in addition to a specific baseline concept. The two baseline flight displays, BSBG and BRD, were approximately split evenly within subject pilot groups. In addition to display type variations, for the approach maneuver a tunnel-off condition was evaluated for the CCFN texture with the 30 arc-sec DEM concept. All display concepts were randomized among the pilots for each maneuver.

Evaluation maneuvers were blocked (high altitude en route, low altitude en route, or approach) with DCs being randomized to counter pilot variability and learning and fatigue effects. The high altitude en route block was always conducted first, then the low altitude en route block, followed by the approach block. The rare event maneuver was conducted at the end of the approach block.

Simulation Operations

The experiment was conducted during a 2.5-month period of time with no substantial schedule interruptions. Each pilot participated in approximately two days of testing, consisting of 35 trial runs. Before the start of the experiment, each pilot received an extensive pilot briefing, as well as approximately one-hour of training time in the GAWS with a FAA certified flight instructor for instruments (CFII). The goals of these briefings and training were to familiarize each subject with the objectives of the experiment and educate the subjects on the salient features of the symbology and simulator functionality. EPs were informed as to which DC they were evaluating prior to each run.

Eleven trial runs were performed for the high altitude and low altitude en route maneuver blocks. Twelve trial runs were performed for the approach block, including the tunnel off CCFN30 run. As previously stated, the single rare event was typically the last run of the experiment for each subject pilot. A total of 945 trial runs were accumulated.

Data Analyses and Results

Due to the vast amount of data recorded and analyzed in this experiment, it is not practical to report on every significant aspect of the simulation in this paper. This document provides a preview of results by evaluating current technology (basic round dials) as it compares to the next level of display concept, an integrated PFD (blue sky/brown ground), and continuing to the comparison of the SVS-PFD display concepts, almost exclusively for the approach maneuver.

Several subjective measures were recorded to estimate levels of workload and situation awareness during the TP-HDD experiment. In addition to subjective measures, performance data such as flight path error and pilot control activity were also recorded and analyzed.

Qualitative Data, Approach Maneuver

Questionnaires were administered at the completion of each trial run, at the end of each maneuver block, and at the conclusion of the experiment. These questionnaires consisted of different techniques, ratings, and questions to solicit specific information regarding SA, mental and physical workload, terrain awareness, and preferences. Run questionnaires included the NASA Task Workload Index (TLX), a Situation Awareness Rating Technique (SART), a terrain awareness measure, a stress measure, and Cooper-Harper Rating elements. Post-block questionnaires included Situational Awareness Subjective Workload and Relative Dominance measures.

Additionally, the block questionnaires and the final questionnaire also dealt with preferred FOVs, terrain information as provided by the MX-20 and PFD, the value of the guidance tunnel (for approach), and other issues.

The qualitative preference for the different SVS display concepts was evaluated by rank-ordering each display concept (except the CCFN30, no tunnel case) for specific maneuvers. The BRD and BSBG were grouped together. Table 2 shows the averages of these rankings for the approach maneuver only.

Table 2. Ranked Display Concepts, Approach

Rank	Actual Mean	Display Concept
1	2.67	EBG1
2	2.70	PR1
3	3.15	PRFN1
4	3.30	EBGFN1
5	5.04	EBGFN3
6	5.15	PRFN3
7	7.22	EBGFN30
8	7.30	PRFN30
9	8.59	CCFN1
10	9.96	CCFN30
11	10.93	Baselines

A non-parametric test was conducted on each set of data to determine statistical significance and selected case pairs were further investigated individually using a related samples procedure (Wilcoxon test). For the approach maneuver, subjects consistently ranked the two CCFN terrain portrayals and the baseline concepts as the least preferred display concepts. Another statistically significant division occurred between the 1 and 3 arc-sec DEMs for the EBG and PR textures. In conclusion, although minor preference variations occurred, statistically, the EBG1, PR1, EBGFN1, and PRFN1 concepts are interchangeable; EBGFN3 and PRFN3 are comparable; and EBGFN30 and PRFN30 are also interchangeable. In addition, statistical results show that CCFN1 was consistently ranked higher than CCFN30, which in turn was consistently ranked higher than the baseline concepts.

Terrain awareness data is also presented in this report for all of the display concepts evaluated during the approach maneuver (figure 10). Terrain awareness was assessed by EPs subjectively rating the level of terrain awareness each concept provided, using a scale of low terrain awareness (0) to high terrain awareness (10).

Figure 10 illustrates the level of increased terrain awareness for all DCs. A statistical analysis indicates that the effect of DC was highly significant. Subsequent post-hoc analysis revealed that the two baselines had lower terrain awareness levels and were significantly different than all of the SVS display concepts, in terms of terrain awareness. Additionally, while the CCFN1 and the CCFN30 DCs produced higher values of terrain awareness than the baselines, these display concepts were still significantly different than the rest of the SVS DCs. The post-hoc analysis also provided data that showed that while all SVS DCs supplied sufficient terrain awareness, they don't convey similar amounts of terrain awareness information. The PRFN30 DC yielded a higher terrain awareness level than the CCFNs, but significantly lower level than the two highest resolution EBGs. While it appears that all the SVS DCs are viable, texture and resolution combinations are important. Results from this statistical analysis indicate that for the EBG texture, DEM resolution doesn't matter, whereas for the PR texture, DEM resolution is a contributing factor in terrain awareness (hence the lower rating of the PRFN30 concept). Only at the lower resolution DEMs do the differences between EBG and PR become evident. The post-hoc results agreed with pilot comments that for the low resolution DEMs, the coloring of the EBG was very intuitive and provided more information than the consistently green color (due to vegetation) of the PR textures. EPs also indicated that in general the EBG textured DCs provided terrain information that was more intuitive and easier to interpret, agreeing with information contained in reference [11]. Specific pilot comments reflected a desire to know when they were approaching a ground-based hazard without a need to know whether it was rocks, dirt, or trees. Additionally, pilots indicated that while the 3 arc-sec DEM will be more than sufficient for GA applications, the 1 arc-sec DEM was still the preferred database resolution. The EPs also generally agreed that while the PR texture provided a “pretty picture”, the EBG texture was easier to decipher in terms of terrain undulations.

With regard to the FN overlay, pilot comments varied. Some of the EPs stated that the FN provided a great enhancement in terrain definition. Other EPs suggested that the FN detracted from the terrain portrayal, for reasons such as the FN being easily mistaken for roads and rivers. In general, EPs indicated that they would not “pay” much for the FN option.

One of the subjective ratings that will be discussed in terms of display type (versus display concept) is the SART. The SART measure was calculated based on a combination of individual ratings of certain characteristics, such as understanding of the situation and demand on attentional resources. Figure 11 illustrates the SART rating for the approach maneuver and how the different pilot groups rated each display type. In general, the low-time VFR- and IFR-rated pilots indicated that the biggest improvement in situational awareness occurred between the BRD and PFD, mostly reflecting the benefits of the tunnel in the sky guidance (rather than information integration), with a similar level of improvement with the addition of terrain on the SVS-PFD. Pilot opinion varied when comparing the BRD to the PFD, with more experienced pilots appearing to be more comfortable with the traditional gauges than the less experienced pilots. Most of the EPs commented that the velocity vector/guidance tunnel combination greatly enhanced their ability to fly an ILS approach. All pilots remarked that the presence of terrain on the head-down display enhanced their overall SA, increasing pilot comfort level almost as much as the improvement observed for the PFD over the BRD. This is a powerful result, indicating the level of SA improvement due to the presence of terrain on the PFD is approximately equal to the dramatic improvement created by a PFD with guidance tunnel.

Another subjective measure that is discussed in terms of display type is the NASA TLX rating. The TLX rating estimated workload through a combination of the individual ratings of mental demand, physical demand, temporal demand, pilot performance, effort, and frustration. In general, the TLX data indicates that the low-time VFR- and IFR-rated pilots noted a substantial workload decrease between the BRD and PFD, as well as a smaller (but still sizeable) decrease from the PFD to the SVS PFD (Figure 12). These TLX data complement the SART data, suggesting that when the terrain portrayal is added to the PFD, all pilots gained improved SA and an associated decrease in perceived workload, when compared to flying with the BRD.

Quantitative Data

Performance data, such as lateral and vertical path error, glide-slope and localizer error, altitude, heading, bank angle, and airspeed errors were also collected and analyzed during the experiment. In addition to the parameters mentioned above, other factors recorded were pilot control inputs, including FOV settings and pitch (longitudinal input), roll (lateral input), and yaw (directional input), along with throttle settings.

Approach Maneuver

To effectively analyze pilot performance, segment analysis of the evaluation maneuvers was conducted. In addition, flight performance was grouped (based on task instructions to the EPs) into “desired” and “adequate” performance ranges. For the final approach task (tracking localizer and glide slope) of the approach maneuver, desired performance was maintaining +/- 10 kts of airspeed error, +/- 1 dot of localizer error, and +/- 1 dot of glideslope error. Adequate performance was considered to be twice desired limits.

Figure 13 shows the mean percent of time the pilots flew within desired performance of the final approach task. As anticipated, the less experienced VFR pilots had difficulty flying a precision approach using the BRD, achieving the desired performance less than 40% of the time, demonstrating the fact that this category of pilots could not safely perform these types of pilot tasks with conventional instrumentation. Low-time IFR-rated pilots accomplished desired performance approximately 63% of the time, achieving minimal acceptable performance (as defined in this experiment) using the BRD. The high-time pilots maintained desired performance using the BRD nearly 90% of the time. An increase in pilot performance was achieved for all pilots when flying with the PFD and SVS-PFDs in the presence of a guidance tunnel with minimal training. When using either the PFD or the SVS-PFDs, the low-time VFR-rated pilots were able to fly as well as the high-time pilots did using the BRD. In addition, when terrain was added to the PFD the impact to performance level for all pilot groups was negligible, although the previously discussed qualitative results indicated greatly enhanced situation awareness and decreased workload with terrain present.

As shown in Figure 14, detailed examination of the flight performance shows that glide slope tracking is the most sensitive performance measure. Airspeed control was not an issue for the EPs during the approach maneuver. In terms of performance, while using the PFD or the SVS-PFD the low-time pilots were able to track the glide slope as well as or better than the high-time pilots did when using the BRD. For a comprehensive analysis of these data in terms of safe performance standards, it is recommended that this evaluation be expanded to include the application of the FAA Instrument Rating Practical Test Standards [13] metrics, incorporating maximum and minimum values as well as histograms of these glide slope data.

Analyses were conducted on pilot control inputs using the standard deviations of pilot pitch, roll and throttle control. The physical workload (as defined by the standard deviations pilot control activity) variations were small between the BRD and the two PFDs. Therefore, pilots were able to realize a significant improvement in pilot performance without compromising the physical workload associated with flying.

For the conditions reported in this paper, flight path control was improved with the PFD and SVS-PFD concepts. Although these data are not shown, different terrain presentations did not appear to impact flight performance in this study. The improvement in performance from the BRD to the PFD and SVS-PFD concepts was attributed to the advanced symbology (velocity vector, tunnel-in-the-sky, etc.) associated with these advanced PFDs. Other analyses were conducted (and are continuing) regarding the various SVS terrain portrayal concepts tested.

Rare Event Maneuver

The measure analyzed for the rare event maneuver was based on the actual time at which the subject first mentioned that something was amiss (i.e., the terrain looks too close). This maneuver was developed with the assumption that all EPs flying the baseline displays would experience CFIT in this rare event, without SVS display of terrain. The results were separated into four categories. Category A contains those subjects who were very aware of their surroundings, and indicated well in advance that they felt there was something amiss. The subjects in Category A were judged to be in a safe position and had plenty of time to maneuver to steer clear of terrain. Subjects who identified that something was amiss, but did so either within 500 ft or 5 seconds of impact were placed in Category B. Category B was designated Controlled Flight Into Terrain "incidents" – not necessarily a crash, but definitely a safety of flight concern. Category C indicated subjects who identified that something was amiss, but were first cued by out the window information (visibility on the OTW display was one statute mile), rather than their instrument displays. And, finally, Category D represented subjects who actually flew into terrain. Table 3 summarizes the results, grouped by pilot experience.

Table 3. Summary of Rare Event Maneuver Categorizations Results

Category	Low-Time VFR	Low-Time IFR	High-Time	Total
A	9	5	4	18
B	0	1	2	3
C	3	0	1	4
D	2	0	0	2

In summary, for 18 out of 27 runs (67%), EPs noted that something appeared to be wrong well within the safe zone. EPs that fell within category B, while safety of flight was a concern, did avoid terrain. So, combining categories A and B, 78 % of the EPs avoided a CFIT using SVS PFDs. Twenty-two percent (combining Categories C and D) of the runs did result in hazardous conditions. These data suggest that training on the use of SVS PFDs for CFIT prevention is necessary. Also these data may reflect that rare event testing is challenging and some pilots may have observed something was wrong, but didn't verbalize it, or delayed verbalizing it.

FOV Results

In general, the pilots agreed that the most preferred FOV setting was approximately 60°. In some circumstances (short final), a narrower FOV was typically preferred. When asked which two FOVs they would prefer in their aircraft, the majority of the EPs selected the FOVs of 60° and 22°.

Conclusions

While flight performance was not significantly affected by various terrain portrayal concepts created through DEM or texture combinations, terrain information of any combination tested in this experiment on a PFD proved to be valuable in terms of situation and terrain awareness. Pilots consistently ranked EBG and PR concepts approximately equal and always higher than the CCFN (which was always rated slightly better than the baseline displays). However, pilot comments indicated that the EBG was more easily deciphered in terms of terrain variations than the PR texture. Since PR concepts require specialized computer-graphics resources that exceed current certified flight computer platforms, EBG concepts are therefore recommended. In addition, while higher DEM resolutions were preferred, pilot comments were received indicating that 3 arc-sec data was nearly as good as 1 arc-sec DEM. As a result, high-resolution DEMs may not be required for sufficient SA from SVS displays. Lastly, the secondary FN texturing concept received mixed ratings with some pilots finding the information that the FN provided to be useful and others determining that the FN was a distraction. None of the EPs commented that they would pay much for the FN option. In general, pilots preferred FOVs of 60° for most of the experiment maneuvers.

In conclusion, with minimal training, PFDs with tunnel guidance improved performance over that exhibited using the traditional displays for the low-time VFR- and IFR-rated pilots. Furthermore, this experiment demonstrated that when terrain is added to the integrated PFD, situation awareness for the pilot was drastically enhanced and mental workload decreased, with no degradation in pilot performance or addition of physical workload. The benefits of the PFD with guidance tunnel could be described as a major contribution to pilot performance developed during the past several decades. Due to the improvement of pilot performance with integrated displays, along with the increased situation awareness inherent in SVS displays, pilots will have enhanced capabilities to avoid CFIT events, making flying significantly safer.

Results from this study were extended and confirmed through flight-testing. It is highly recommended to combine simulation and flight-test efforts in this manner to optimize resources.

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[13] FAA Instrument Rating Practical Test Standards

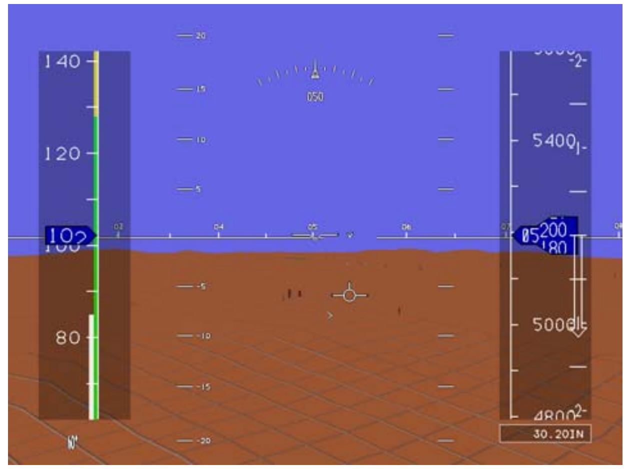

Figure 1. CCFN30 Display Concept.

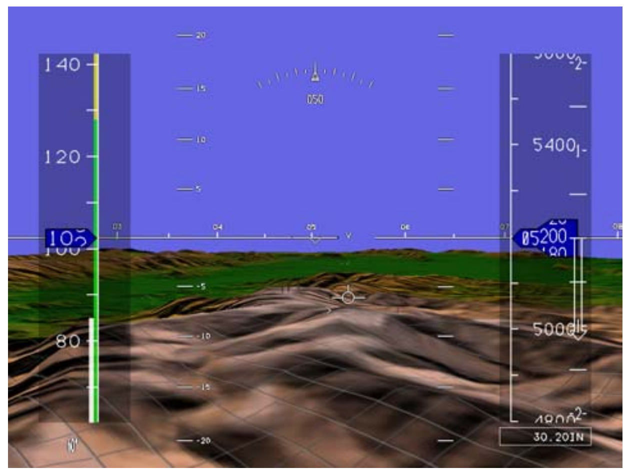

Figure 2. EBGFN3 Display Concept.

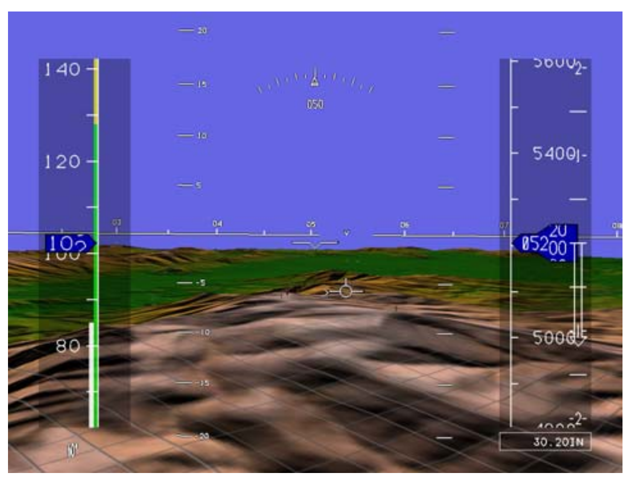

Figure 3. EBGFN30 Display Concept.

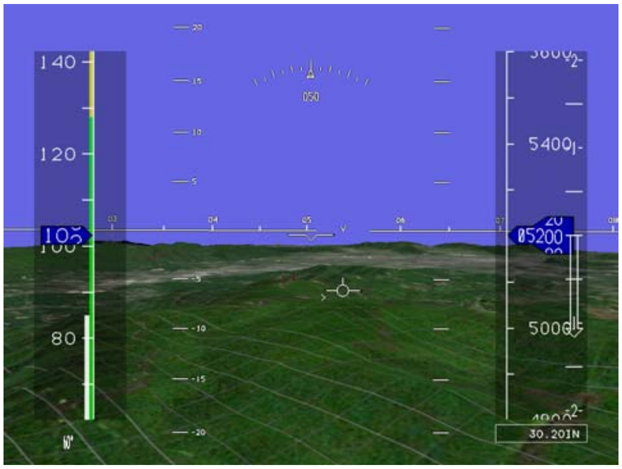

Figure 4. PRFN3 Display Concept.

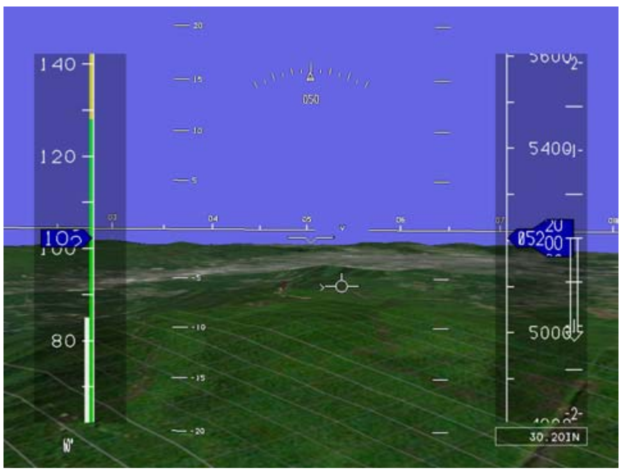

Figure 5. PRFN30 Display Concept.

Figure 6. Baseline Round Dials (BRD).

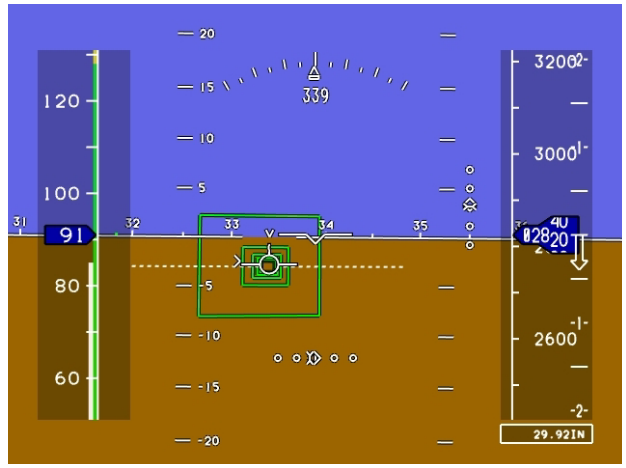

Figure 7. Blue Sky/Brown Ground (BSBG).

Figure 8. Photo of MX20 During ROA Approach Maneuver.

Figure 9. GAWS Facility.

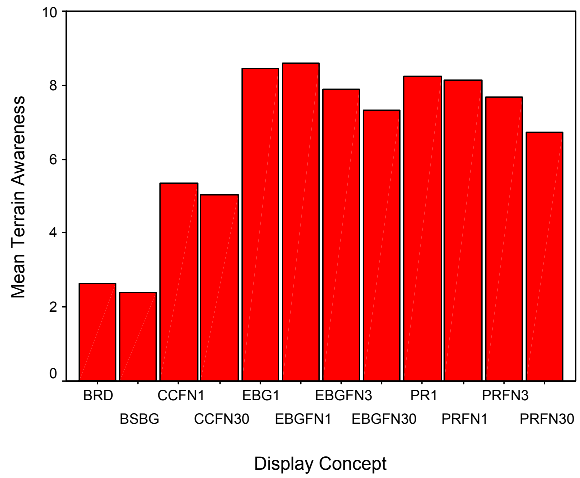

Figure 10. Terrain Awareness for all DCs Tested.

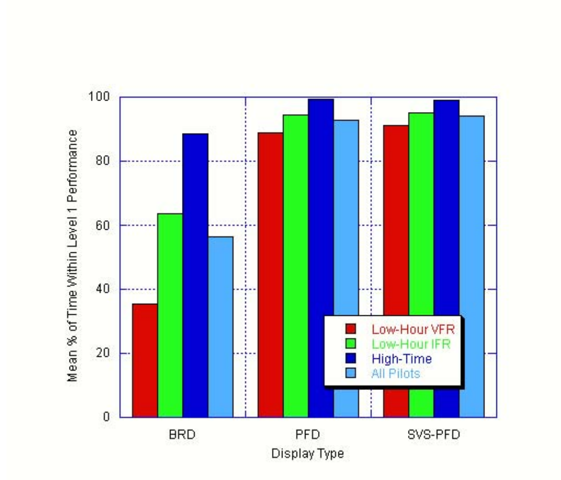

Figure 13. Desired Performance, Final Approach.

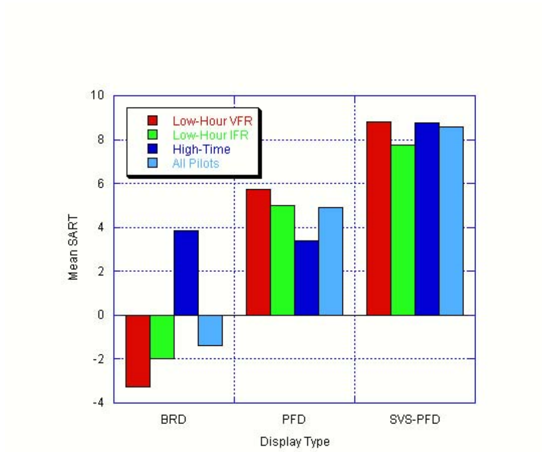

Figure 11. SART Rating For Display Types.

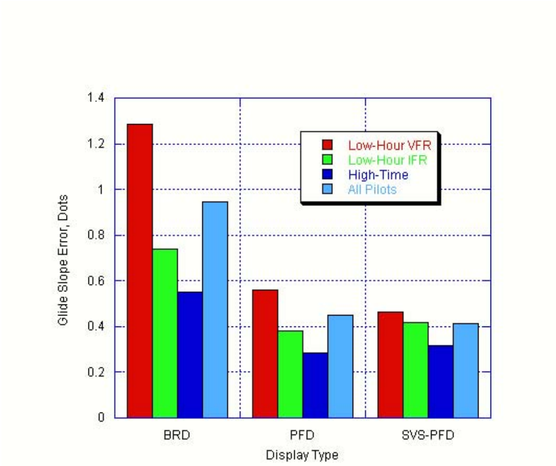

Figure 14. Glide Slope RMS Error, Segment 7.

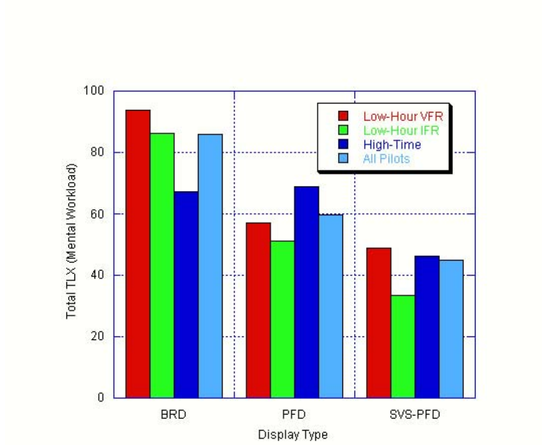

Figure 12 TLX For Display Types.